SPECTRAL DECOMPOSITION OF SEISMIC DATA WITH IMPROVED SYNCHROSQUEEZING TIME-FREQUENCY TRANSFORM

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ABSTRACT

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Spectral decomposition is a novel signal analysis tool for seismic data. Resolution of traditional time-frequency transform methods is limited by Heisenberg uncertainty principle. By assigning complex coefficients along frequency or scale axis, synchrosqueezing algorithm is a way to sharpen time-frequency representation towards its ideal representation. Whereas, traditional synchrosqueezing algorithm is not very suitable for signal which contains strong frequency modulated modes. Time-frequency respresentation needs to be further sharped to meet the needs of seismic signal analysis and interpretation. In this paper, we introduce an improved synchrosqueezing algorithm named second-order synchrosqueezing transform into seismic spectral decomposition. With computation of second-order derivatives of the phase of STFT, we can obtain an invertible and sharper time-frequency representation than traditional synchrosqueezing algorithm. The method is applied to synthetic signal and field seismic data. Results show its effectiveness.

KEY WORDS: spectral decomposition, synchrosqueezing, sparse, invertible.

INTRODUCTION

The seismic signal is non-stationary due to absorption and attenuation of underground medium. Spectral decomposition is an important tool for seismic signal analysis. Conventional spectral decomposition technique cannot meet the need of seismic processing and interpretation due to its poor resolution. R&D and application of high resolution seismic spectral decomposition method is imminent.

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Short-Time Fourier Transform (STFT) is a powerful tool for seismic signal processing. It has been used widely in seismic processing and interpretation such as noise suppression, absorption attenuation analysis, hydrocarbon detection, etc. (Gridley and Lopez, 1999). However, its time-frequency resolution is limited by the Heisenberg uncertainty principle. Short time window causes poor frequency resolution, and long time window causes poor time resolution. Continuous wavelet transform (CWT) is used to divide a continuous time signal into wavelets, offering a time-scale representation with better time and scale resolution (Hlawatsch and Boudreaux-Bartels, 1992). Relationship between instantaneous frequency and scale of wavelet is not very clear. Wigner-Ville distribution (WVD) and its associated time-frequency analysis method can offer a sparse time-frequency distribution for single component signals. One serious disadvantage of WVD is cross-term interference for complex signals (Sattar and Salomonsson, 1999). Empirical mode decomposition (EMD) is a signal adaptive decomposition method, it does not depend on any base function and can offer a higher time-frequency resolution with Hilbert transform. However, EMD is an experiential approach and does not have strict mathematical physics basis, its stability is affected by intrinsic mode function decomposition (Huang, 1996; Torres et al, 2011; Han and van der Baan, 2013).

Time-frequency reassignment methods can provide a sharper result by assigning spectrogram along time and frequency axis, however it does not allow for signal reconstruction. Combined with synchrosqueezing algorithm, synchrosqueezing transform can provide a sparse and invertible time–frequency map by assigning complex spectrum only along frequency axis. Synchrosqueezing algorithm combines the sparsity properties of ressignment methods with the invertibility of traditional time-frequency transform, and has been applied in seismic signal analysis, channel detection, denoising, etc. (Daubechies et al., 2011; Shang et al., 2013).

However, traditional synchrosqueezing algorithm is not very suitable for signals containing strong frequency modulated modes. Inspired by synchrosqueezing algorithm, an improved synchrosqueezing method named vertical second-order synchrosqueezing transform (VSST) is proposed with a new local estimation of instantaneous frequency. This new synchrosqueezing process uses the second-order derivatives of the phase of the short-time Fourier transform, and provides a better time-frequency map for complex signals. We introduce it into seismic data analysis, results show its effectiveness.

THEORY

The short-time Fourier transform (STFT) of signal $f \in L^2(R)$, with respect to the analysis window g is defined by

$$V_f^g(\eta,t) = \int_R f(\tau) g(\tau - t) e^{-2i\pi\eta(\tau-t)} d\tau = A(\eta,t) e^{i2\pi\Phi(\eta,t)} \qquad (1)$$

$\left|V_f^g(\eta,t)\right|^2$ is called the spectrogram, $2\pi\Phi(\eta,t)$ represents the phase of STFT.

Obviously, $V_f^g(\eta,t)$ is a tradeoff between time and frequency resolution. $\left|V_f^g(\eta,t)\right|^2$ can be viewed as the 2D smoothing of the WVD by the analyzing window and provide a smearing time-frequency energy distribution (Auger, et al., 2012) . In order to sharpen the TF representation, reassignment technique (Flandrin et al., 2003; Auger and Flandrin, 1995; Auger et al., 2013) is proposed by assigning the local TF spectrogram $\left|V_f^g(\eta,t)\right|^2$ according to the map $(\eta,t)\rightarrow(\hat{\omega}_f(\eta,t),\hat{t}_f(\eta,t))$:

$$\hat{\omega}_f(\eta,t)=\eta-im(V_f^{g'}(\eta,t)/V_f^g(\eta,t)) \quad , \tag{2}$$

$$\hat{t}_f(\eta,t)=t+re(V_f^{tg}(\eta,t)/V_f^g(\eta,t)) \quad , \tag{3}$$

$$S_f(\omega,t)=\iint_0^\infty\left|V_f^g(\eta,t)\right|^2\delta(\omega-\hat{\omega}_f(\eta,t))\delta(\omega-\hat{t}_f(\eta,t))d\eta dt \quad , \tag{4}$$

where $S_f(\omega,t)$ represents the reassigned spectrogram. $\hat{\omega}_f$ is an approximation of the instantaneous frequency and $\hat{t}_f$ is the group delay. im and re represent imaginary part and real part. $V_f^{tg}(\eta,t)$ and $V_f^{g'}(\eta,t)$ are the spectrum of the STFT with analysis windows
$tg(t)=t\times g(t)$ and $g'(t)=\partial g(t)/dt$.

Although reassignment algorithm can provide a shaper TF representation by assigning time-frequency energy along time and frequency axis, signal cannot be recovered from this method. STFT-based synchrosqueezing transform (FSST) was proposed to provide a sparse and invertible time-frequency map by neglecting operator $\hat{t}_f$ and only reassign the complex coefficients $V_f^g(\eta,t)$ according to the map $(\eta,t)\rightarrow(\hat{\omega}_f(\eta,t),t)$ defined by Oberlin et al. (2015):

$$\begin{aligned}\hat{\omega}_f(\eta,t)&=\frac{1}{2\pi}\partial_t\arg V_f^g(\eta,t)\\&=\partial_t\Phi(\eta,t)\\&=\eta-im(V_f^{g'}(\eta,t)/V_f^g(\eta,t))\end{aligned} \quad , \tag{5}$$

$$T_f(\omega,t)=\frac{1}{g(0)}\int_0^\infty V_f^g(\eta,t)\delta(\omega-\hat{\omega}_f(\eta,t))d\eta \quad , \tag{6}$$

where $\hat{\omega}_f(\eta,t)$ is an approximation of the instantaneous frequency, $T_f(\omega,t)$ is FSST result. By relocating complex coefficient $V_f^g(\eta,t)$ instead of spectrogram $\left|V_f^g(\eta,t)\right|^2$, synchrosqueezing algorithm enables to recover signals which is not possible with reassignment algorithm.

For a simple signal $f(t) = ae^{i2\pi\phi(t)}$ with $\phi''(t) = 0$ for all t, one exactly has $\phi'(t) = \hat{\omega}_f(t,\eta)$. So that when ϕ'' is small enough compared with ϕ', the approximation $\phi'(t) \approx \hat{\omega}_f(t,\eta)$ is justified.

The FSST assumes $\phi''(t)$ is negligible, reducing its applicability for signal with high frequency modulation. When dealing with strong modulated signal, the approximation $\phi'(t) \approx \hat{\omega}_f(t,\eta)$ is very inaccurate. Let the signal $f(t) = Ae^{2i\pi\phi(t)}$ be a linear chirp with constant ϕ'', we have (Oberlin et al., 2015; Pham and Meignen, 2017):

$$\begin{aligned}\phi'(t) &= \phi'(\hat{t}_f(\eta,t)) + \phi''(\hat{t}_f(\eta,t))(t-\hat{t}_f(\eta,t)) \\ &= \hat{\omega}_f(\eta,t) + \hat{q}_f(\eta,t)(t-\hat{t}_f(\eta,t))\end{aligned} \quad , \tag{7}$$

$$\hat{q}_f = re\left\{\frac{1}{2i\pi}\frac{V_f^{g''}V_f^g - (V_f^{g'})^2}{(V_f^g)^2 + V_f^{tg}V_f^{g'} - V_f^{tg'}V_f^g}\right\} \quad . \tag{8}$$

We can see that the second order term $\phi''(\hat{t}_f(\eta,t))(t-\hat{t}_f(\eta,t))$ cannot be neglected with strong modulated signal. Replacing $\hat{\omega}$ by ϖ in standard FSST, the vertical second-order synchrosqueezing (VSST) is as follows (Oberlin et al., 2015; Pham and Meignen, 2017):

$$VT_f(\omega,t) = \frac{1}{g(0)}\int_0^\infty V_f^g(\eta,t)\delta(\omega - \varpi_f(\eta,t))d\eta \quad , \tag{9}$$

$$\varpi_f(\eta,t) = \begin{cases}\hat{\omega}_f(\eta,t) + \hat{q}_f(\eta,t)(t-\hat{t}_f(\eta,t)) & if\ \partial_t\hat{t}_f(\eta,t) \neq 0 \\ \hat{\omega}_f(\eta,t) & otherwise\end{cases} \quad , \tag{10}$$

where $\hat{t}_f$ is the group delay, $\varpi_f(\eta,t)$ is second-order instantaneous frequency estimator.

VSST SPECTRAL DECOMPOSITION OF SEISMIC DATA

In order to demonstrate the effectiveness of this method in seismic data analysis, tests are performed.

Example 1

The synthetic signal (Fig. 1) is composed of a constant 30 Hz wave from 0 s to 0.6 s, a 40 Hz Ricker wave at 0.8 s, and a wave from 0 s to 0.6 s with strong frequency modulation.

Both STFT and VSST methods were applied to this synthetic data. Fig.2 shows the ideal time-frequency map of synthetic signal. Fig. 3 shows STFT result, although STFT can reveal all components of this signal, its resolution is limited by Heisenberg uncertainty principle. High time resolution leads to a poor frequency resolution.

Fig. 4 shows the TFR produced by the FSST approach. Through reallocating the complex value of STFT along frequency axis, a sparse TFR is produced, improving the frequency resolution with the same time resolution. However, instantaneous frequency estimation of FSST is not suitable for signal with high frequency modulation. The frequency resolution of Ricker wave at 0.8 s and the modulation wave from 0 s to 0.6 s needs to be improved further. Fig. 5 shows the enhanced TFR produced by the our VSST method, with a new instantaneous frequency estimator, all components of this synthetic signal are characterized better with a higher resolution in VSST time-frequency map. The reconstructed signal from the VSST time-frequency map is shown in Fig. 6, the signal can be well recovered due to its invertibility.

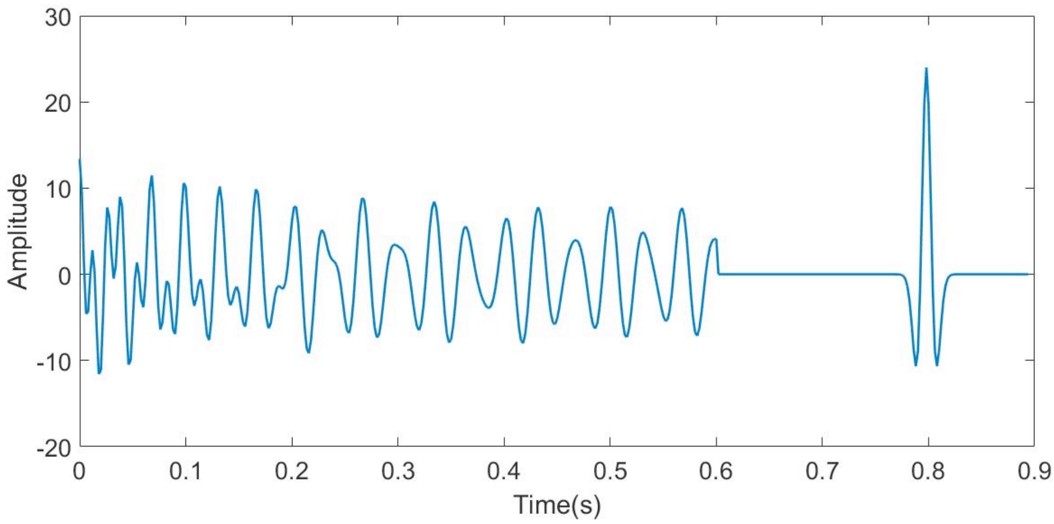


Fig. 1. The synthetic signal: a constant 30 Hz wave from 0s to 0.6 s, a 40 Hz Ricker wave at 0.8 s, and a wave from 0 s to 0.6 s with strong frequency modulation.

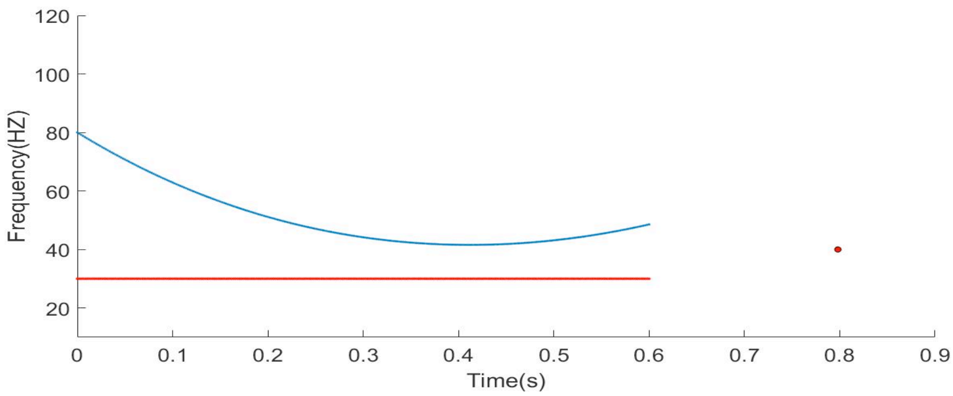


Fig. 2. Ideal TF representation of synthetic signal.

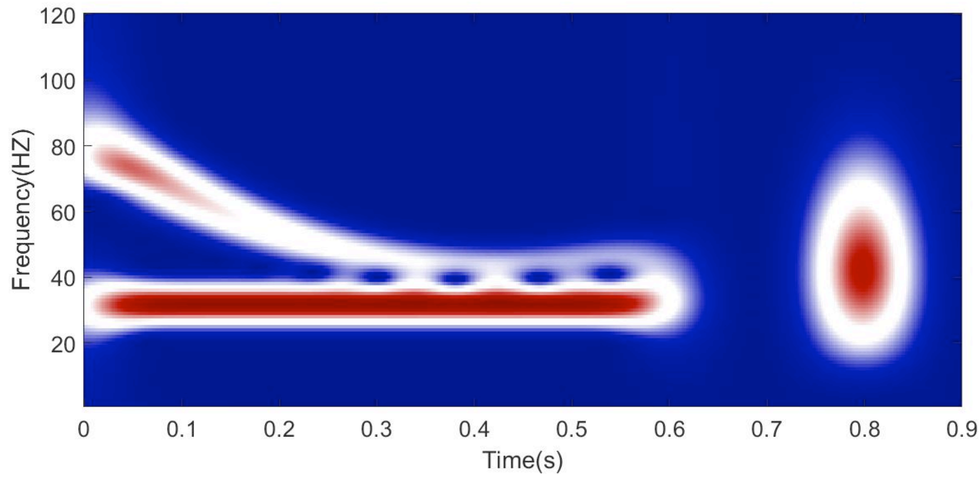


Fig. 3. TFR obtained by STFT transform, its resolution is poor.

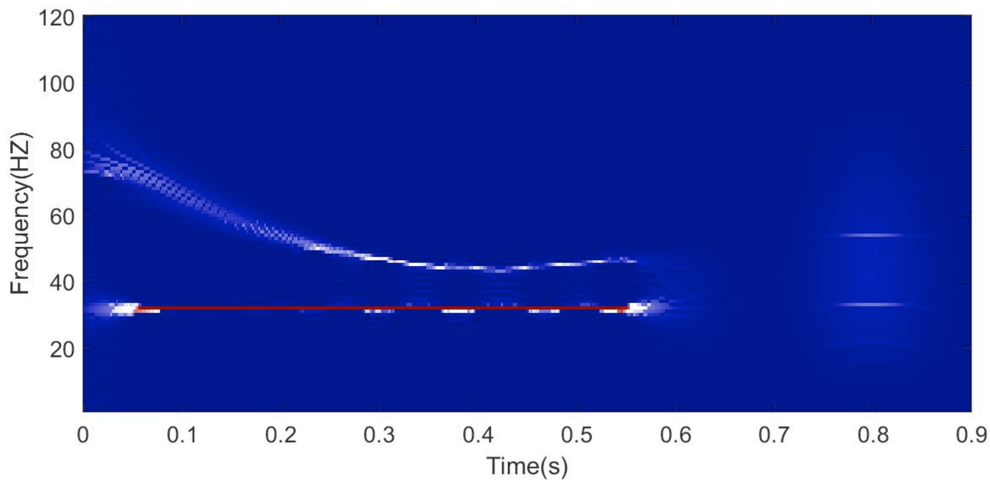


Fig. 4. TFR obtained by FSST transform, although TF resolution is improved for constant frequency wave and weak frequency modulation wave, the resolution of signal with strong frequency modulation is still poor. Especially for the Ricker wave at 0.8 s.

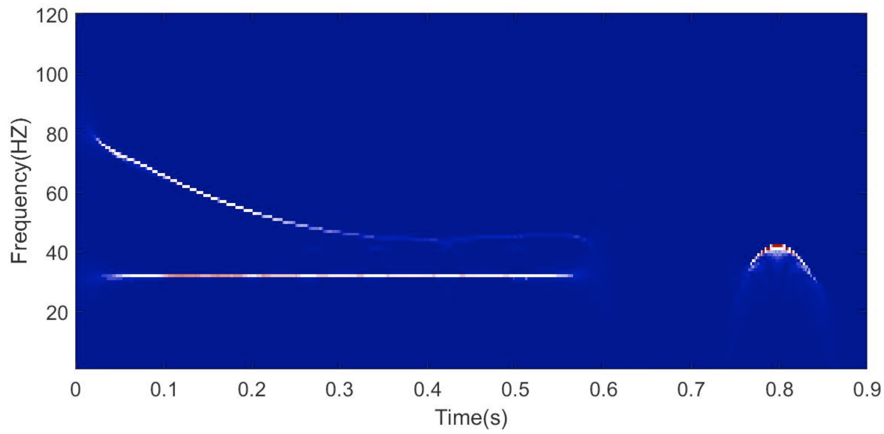


Fig. 5. TFR obtained by VSST transform, providing a better result.

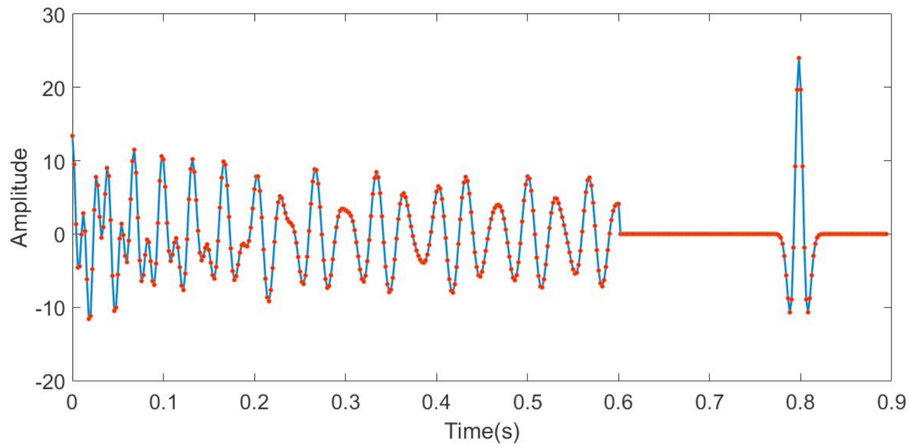


Fig. 6. Signal reconstruction from VSST TFR shown in Fig. 5. Blue line represents the original signal and red dots represent the reconstructed signal.

Example 2

A trace of field seismic data is shown in Fig. 7. Fig. 8 shows the STFT time-frequency map, its resolution is limited by Heisenberg uncertainty principle. The VSST result is shown in Fig. 9, it is obviously that VSST method performs better with higher resolution.

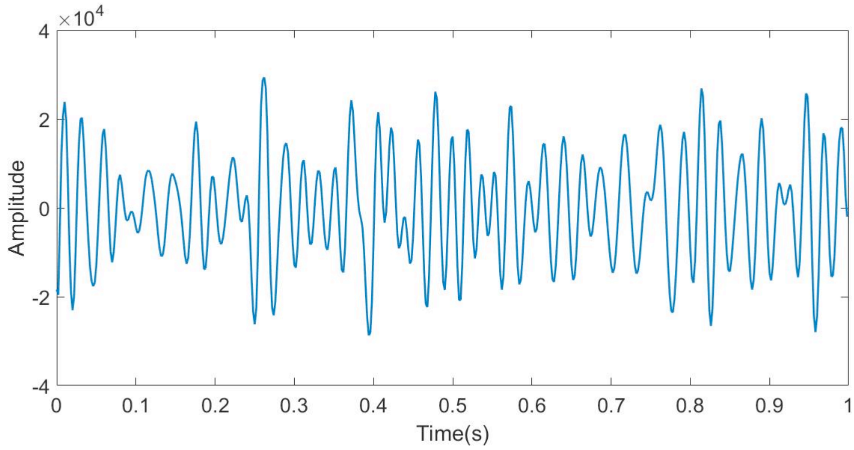


Fig. 7. Field seismic trace.

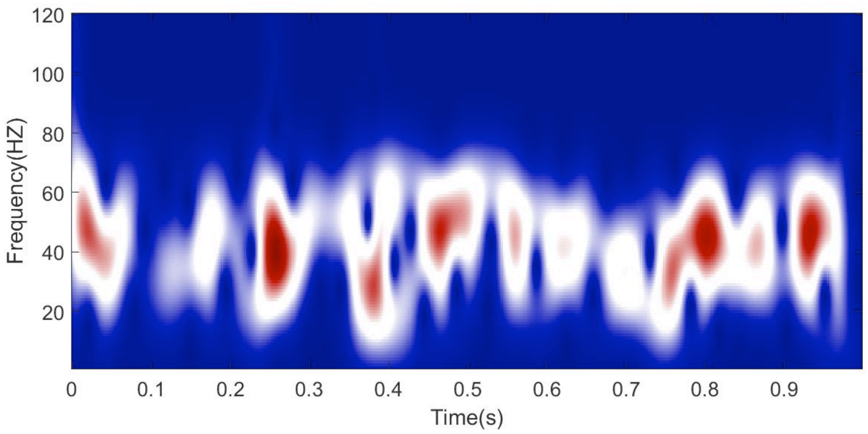


Fig. 8. TFR obtained by STFT transform.

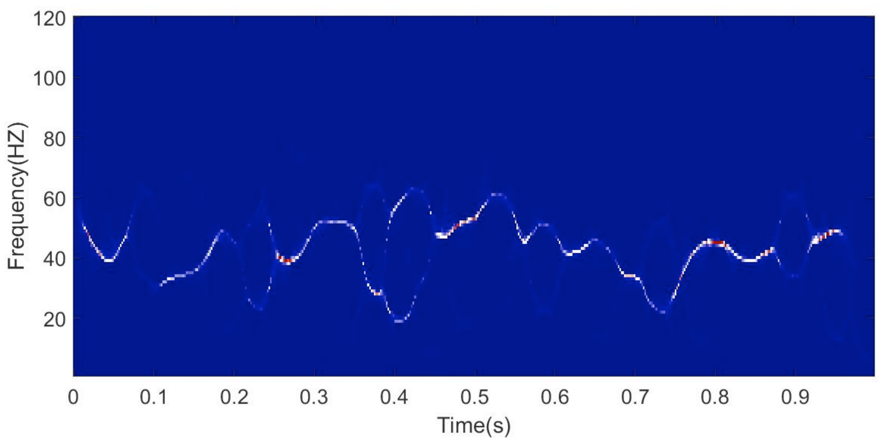


Fig. 9. TFR obtained by VSST transform, providing a sparse time-frequency map.

HYDROCARBON DETECTION BASED ON VSST SPECTRAL DECOMPOSITION

It is known that when a seismic signal penetrates through hydrocarbon reservoirs, its amplitude will show abnormal, its high-frequency components will be attenuated more than low-frequency components. Spectral decomposition has been widely used in reservoir hydrocarbon detection, and in its practical application, the accuracy of spectral decomposition is critical important.

Considering the high resolution of VSST, hydrocarbon detection with this method was applied to field seismic data, its effectiveness was verified.

Fig. 10 shows the connecting-well seismic section and its fft spectrum. Drilling results reveal that the reservoir formation thickness decrease from left to right (well 1 ~ well 4). Only well 2 and well 3 meets industrial oil. It is obviously we cannot get reliable prediction only utilizing the strength of amplitude. Weak amplitude at well 1, 4 locations meets water, whereas weak amplitude at well 3 location meets oil formation. Spectral decomposition is often applied to reveal hydrocarbon reservoir, oil and gas reservoirs often show strong low frequency anomaly and weak high frequency energy. Both STFT and VSST methods were carried out. Results show the reliability of our new method.

Fig. 11 shows frequency slices of seismic data obtained by STFT method. The oil-rich zones at well 2 show strong amplitude anomaly in the low-frequency slice (Fig. 11a, 20 Hz) and weak amplitude in the high-frequency slice (Fig. 11b, 55 Hz). Due to resolution of STFT, we can't predict accurately if it’s oil-rich or not at well 1\3\4 locations by using low-frequency anomaly.

Frequency slices obtained by VSST method are shown in Fig. 12.

Thanks to the high resolution of VSST, Clear and strong low-frequency anomaly of oil reservoir at well 2 and well 3 is shown in Fig. 11a. Weak low-frequency anomaly at well 1 and well 4 indicate that there may doesnot exist oil or gas reservoir.

Actual application results show that VSST can character oil reservoir better due to its high resolution, reducing uncertainty in reservoir fluid detection with traditional spectral decomposition method.

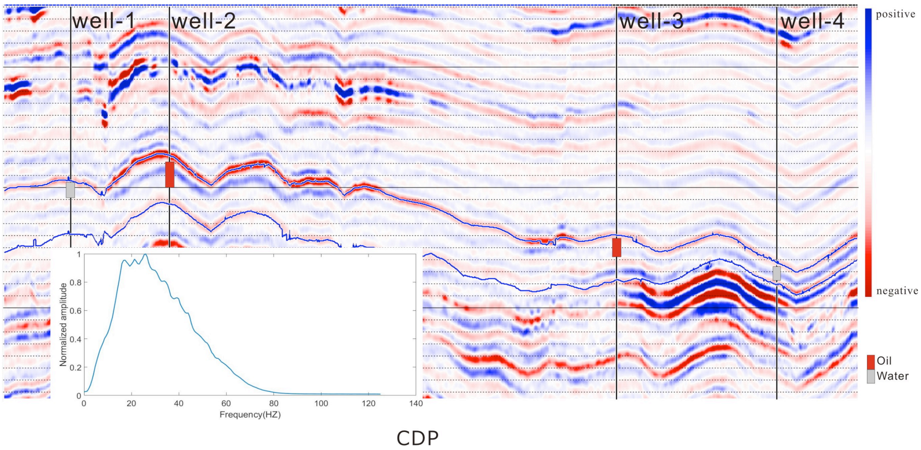
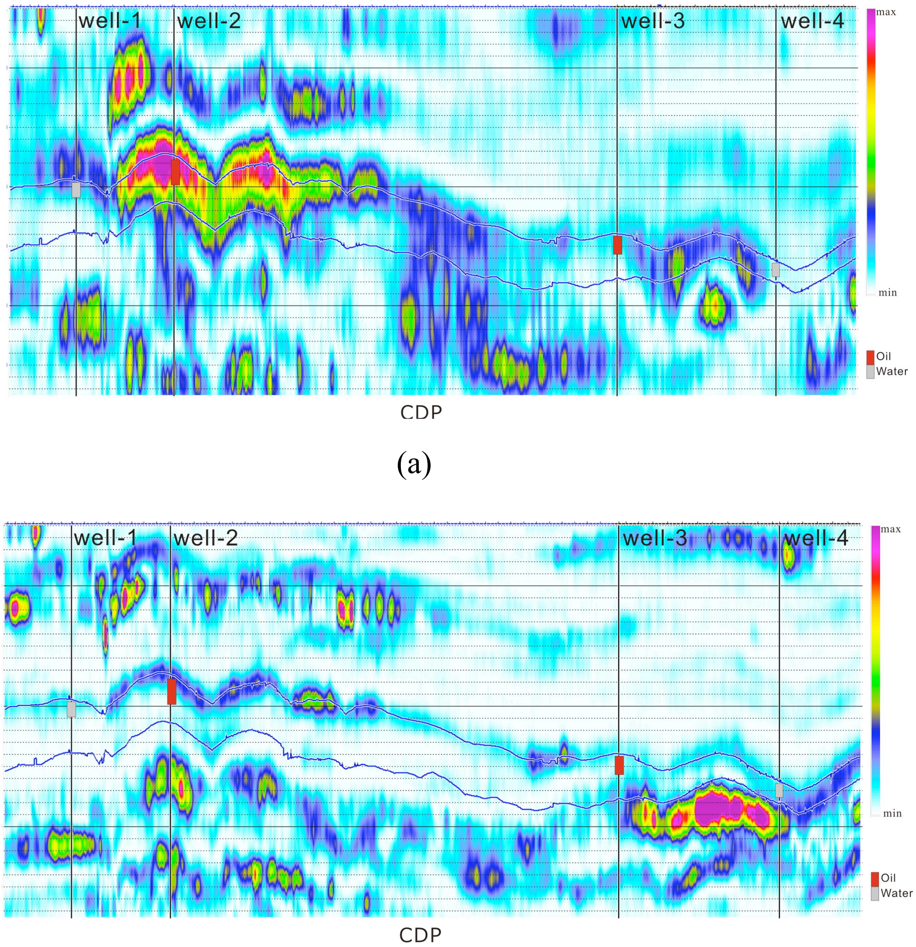
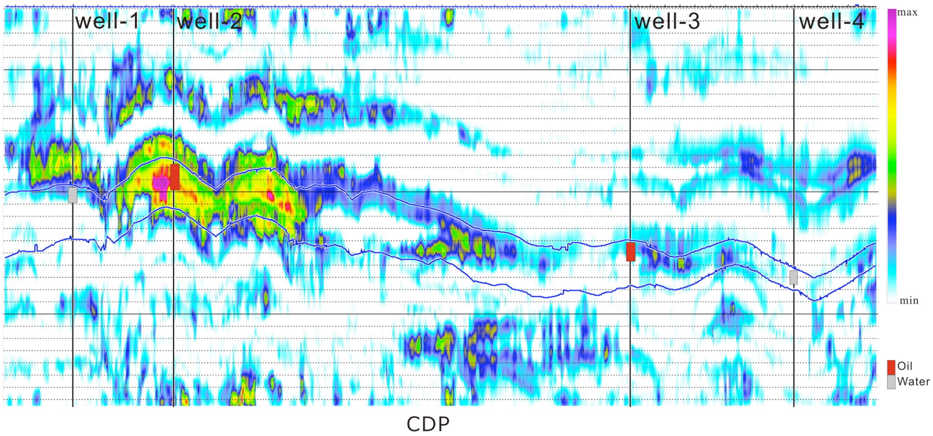


Fig. 10. Connecting-well seismic section and its fft spectrum.

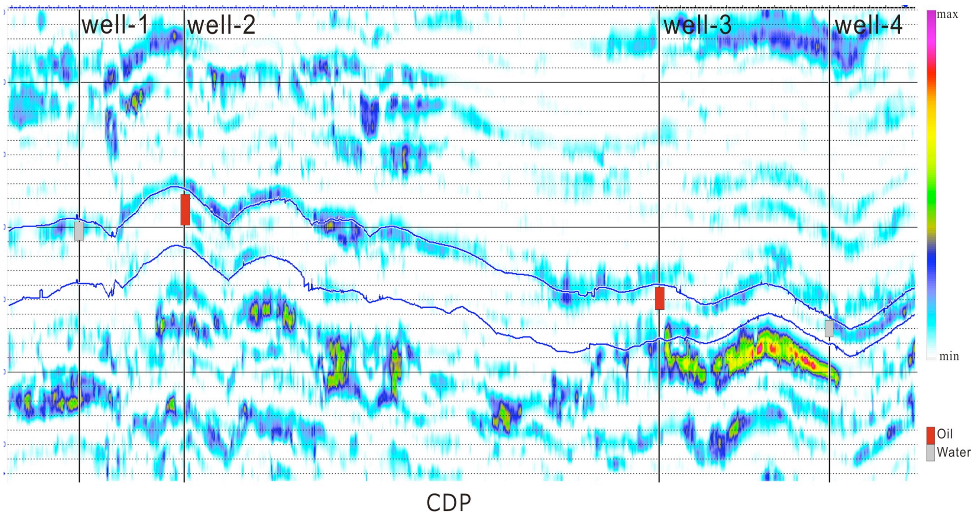


(b)

Fig. 11. Frequency Slices obtained by STFT (a: 20 Hz, b: 55 Hz).



(a)



(b)

Fig. 12. Frequency Slices obtained by VSST (a: 20 Hz, b: 55 Hz).

CONCLUSION

We introduced a sparse and invertible time-frequency method named VSST for seismic data analysis and interpretation. By allocating complex coefficient along frequency axis with a new instantaneous frequency estimator, a new sparser and invertible time-frequency map is provided. Synthetic example shows that it performs better. And then we presented a hydrocarbon detection method based on VSST, the real field example shows that our results meet drilling results well. As a new seismic spectral decomposition method, VSST can also be used further in seismic noise suppression, deconvolution, channel detection, etc.

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